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The effect of biofuel on the international oil market

Author:
Hochman, Gal, University of California, Berkeley and Ben Gurion University, Isreal
Rajagopal, Deepak, University of California, Berkeley
Zilberman, David D., University of California, Berkeley and Giannini Foundation

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Gal Hochman, Deepak Rajagopal,
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1 Introduction

Concerns about energy security and high oil prices, as well as greenhouse gases, led to policies that promoted the use of biofuels (e.g., the American Clean Energy and Security Act of 2009[1]; The European Strategy for Sustainable, Competitive and Secure Energy, 2006[2]). Yet, the effects of the introduction of biofuels on fuel markets are not fully understood. Recent studies on the effect of biofuels assume competitive fuel markets (e.g., Rajagopal et al. 2007; de Gorter and Just 2008), thus ignoring the "elephant in the room," namely, the Organization of Petroleum Exporting Countries (OPEC). This paper introduces an alternative framework to analyze how OPEC operates and responds to growing biofuel use, and applies this framework to estimate the effect of biofuel on the fuel markets. Specifically, we discuss the effect of biofuel on fuel prices, quantity consumed, carbon savings, and the distribution of costs and benefits from biofuel.

Our analysis applies the optimal export tax model (henceforth, cartel-of-nations model or simply CON model), assuming that oil-exporting countries maximize domestic consumer and producer surplus from oil production and fuel consumption, resulting in a wedge between prices in oil-exporting countries and international prices. This wedge equals the optimal export tax. We also assume biofuel presents a competitive fringe, which affects oil-exporting countries' decision making. We then calibrate the model to 2007 data, and estimate that biofuel production in 2007 increased fuel subsidies in OPEC countries by 2%-3%, and it reduced international fuel prices by 2%.[3] On the other hand, the introduction of biofuels caused the annual amount of gasoline consumed to decline by about 1.2 billion gallons a year, i.e., about 0.85% of total consumption. We also compute total reduction in carbon emissions due to the introduction of biofuels, using the average per unit carbon footprints of different fuel feedstock. The benefit from carbon savings under the CON model, given plausible scenarios, are large.

Our analysis shows that using the wrong model, i.e., competitive model or cartel-of-firms (henceforth, COF) model, biases the estimates of the effect of biofuels on fuel markets. For example, and assuming the CON model correctly models the fuel markets, we show that competition overestimates the price effect, but underestimates both quantity and environmental effects attributed to the introduction of biofuels (the environmental effect is underestimated by about 40%). The impact of biofuel on the oil economy is likely to increase in the future as demand will increase. Assuming fuel demand increases by 20%, we estimate that biofuel consumption as well as its effect on prices will double. We also show that increasing demand increases the magnitude of the measurement error resulting from incorrectly assuming a competitive or a COF model.

[1] http://www.govtrack.us/congress/billtext.xpd?bill=h111-2454

[2] http://ec.europa.eu/energy/green-paper-energy/doc/2006_03_08_gp_document_en.pdf

[3] Recall that under the export tax paradigm the marginal cost is equated to demand in exporting countries, but is only equated to marginal revenue in importing countries. Note also that demand is linear, and hence the slope of the marginal revenue curve is two times the slope of the demand curve.

Section 2 below describes the conceptual framework used to model oil-exporting countries, whereas the data used are presented in Section 3. The numerical analysis is presented in Section 4. Policy implications and concluding remarks are given in Section 5.

2 OPEC and biofuel: A conceptual framework

Our objective is to correctly introduce biofuels into fuel markets, recognizing that these markets are dominated by a cartel of oil-rich nations, and that there is a wedge between the price in oil-rich countries and in oil-importing countries. The existing literature on biofuels, as well as literature on food versus fuel, however, assumes biofuels do not influence fuel prices. Fuel markets are assumed to be competitive (e.g., Rajagopal et al. 2009; FAO 2008; Abbott et al. 2008). On the other hand, the literature on crude oil usually assumes a COF model (e.g., Adelman 1982; Griffin 1985).[4] The former literature ignores OPEC, whereas the latter ignores the wedge between domestic and international prices.

Unlike the above models, the CON model does capture the wedge we observe in the data and does model OPEC's pricing behavior.[5] With the CON model, governments in oil-exporting countries set prices to maximize domestic consumer and producer surplus from oil consumption and production. Our baseline model, which we assume to be the correct model, is the CON model, whose predictions we compare to the competitive and the COF models.

Formally, and without loss of generality, we employ a partial equilibrium analysis, focusing on two countries: an oil-rich country (denoted country H) and an oil-importing country (denoted country F). Country F variables are denoted with asterisk (*), country H variables with no asterisk. Fuel can be produced with oil or with a biofuel feedstock. For tractability, we assume oil and biofuel feedstock are perfect substitutes used to produce fuel, measured in terms of its gasoline-equivalent energy content.[6]

Initially, we assume no biofuels. Country H produces Q units of oil, with X units sold domestically and M units sold abroad. The price of oil in country H is p, whereas it is p^* in country F. MC denotes the marginal cost of oil extraction and production.[7]

We contrast three alternative market structures: competitive, COF, and CON models. Whereas the competitive market structure maximizes global welfare, the COF maximizes oil firms' profits.

[4] A few have also argued that OPEC is a revenue-maximizing entity (e.g., Teece 1982); OPEC is driven mostly by political motives (e.g., Moran 1982); and that OPEC core members behave as a dominant, profit-maximizing firm, while other members respond to a different set of incentives (e.g., Alhajji and Huettner 2000).

[5] Hochman and Zilberman (2008) showed, using data on gasoline prices during the late 1990s to early 2000s, that the CON model explains OPEC's behavior well.

[6] The outcome of the partial equilibrium analysis can be extended to include quasi-linear preferences where two commodities are traded, in contrast to one, and the non-oil commodity denotes the numeraire good s whose price we normalize to one.

[7] Dynamic facets of fossil fuel can be introduced to the analysis if, instead of focusing on marginal cost, we focus on user costs. The cost structure can be replaced by user costs, which measures the cost incurred over a period of time as a consequence of extracting crude oil. User costs include the capital, or interest, cost.

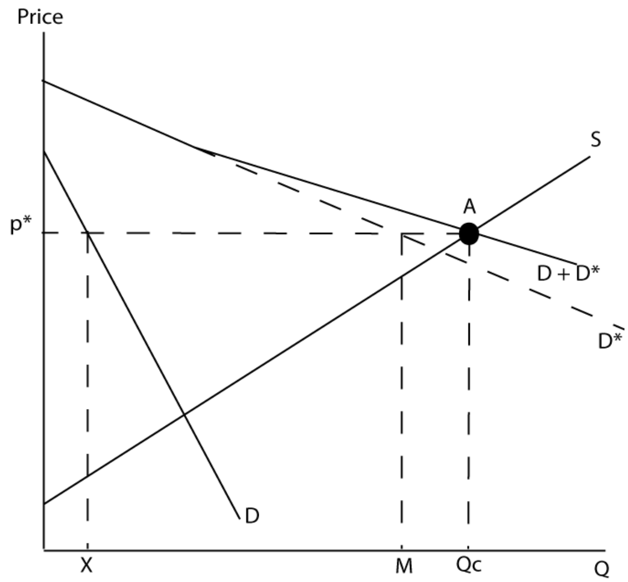

Figure 1: The competitive model

Policy in the CON model, in contrast to the other two models, maximizes oil-exporting countries' economic surplus from oil extraction, production, and consumption.

More specifically, a competitive model maximizes the sum of welfare of country H and country F, and at the global optimum exports taxes equal to zero and $p = p^* = MC$. Given no-transaction costs, the oil prices in H equal the prices in F. If, in addition, firms are price takers, then prices equal the marginal cost of production. The equilibrium outcome is depicted in Fig. 1, where aggregate demand for oil is denoted $D + D^*$, such that the oil-exporting and oil-importing countries' demand functions are D and D^*, respectively. Let S denote supply of fossil fuel, and the equilibrium point, denoted A, is obtained at quantity Q_C and price $p = p^*$.

The COF model, on the other hand, assumes firms collude and form a cartel (see Fig. 2). Then, in equilibrium $MR = \partial R / \partial Q = MC$, and R denotes total revenues. In other words, marginal revenue equals marginal cost and $p = p^* > MC$. When compared to the competitive equilibrium, the COF equilibrium, denoted point B, yields a higher price to both domestic and foreign consumers. Although this theory explains why fuel prices are higher than marginal cost, the COF model does not explain the observed wedge between oil-exporting and oil-importing countries' fuel prices.

Finally, the CON model assumes politicians in the exporting country design the export tax to maximize the sum of its consumers' and producers' net welfare plus export tax revenues. The optimal allocation rule is then derived, assuming firms are price takers and the economy has monopoly power in international markets (captured by points C_Q, C_H, and C_F in Fig. 3). The left-hand part of Fig. 3 depicts consumption, whereas the right-hand side depicts production. The marginal export revenue curve, $MR^* = \partial \left(p^* \cdot M \right) / \partial M$, is added to the domestic demand curve, D, to yield the kink curve $D + MR^*$. The intersection of this curve with the marginal cost curve, S, yields total fuel output,

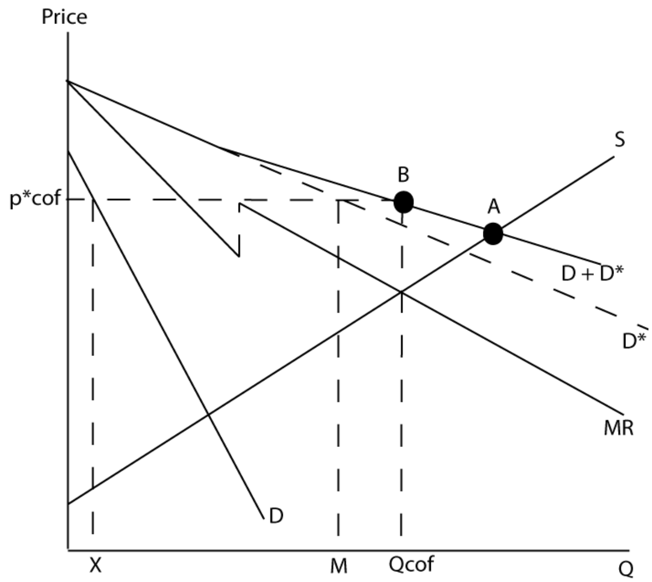

Figure 2: The COF model

Q_{CON}, which results in export and domestic consumption levels, X and M, respectively. In this case, p denotes domestic price and the import price (international price) $p^* > p$. To implement this policy, the export tax should equal $p^* - p$. Such a policy can also be implemented with a quota, Q_{CON}, and a domestic consumption subsidy equal to $p^* - p$. Henceforth, and for simplicity, we focus on an optimal export tax. As noted by looking at Fig. 3, the price paid by country F is lowest under competition and highest under CON. On the other hand, although the quantity is largest under competition, it is lowest under COF, not CON. The reason for the higher output under CON is that domestic consumption in oil-exporting countries is larger and prices lower than the quantity and domestic price with competition and COF.

As the CON model suggests, consumers of gasoline and diesel in oil-rich countries pay a significantly lower price at the pump, compared with the price paid by consumers in oil-importing countries (Metschies et al. 2007). The average super gasoline price for OPEC countries is lower than the price for oil-importing countries. Whereas in 2006 super gasoline prices in non-OPEC countries equaled, on average, 1.04 US$ per liter, it equaled only 0.28 US$ per liter in OPEC countries (Metschies et al. 2007). Moreover, nominal subsidies went up in OPEC countries, at times when crude oil prices surged during 2002 to 2006 (Metschies et al. 2007). A similar pattern is observed for diesel prices, such that diesel prices in non-OPEC countries equal 0.9 US$, but they only equal 0.26 US$ in OPEC countries.

We now introduce biofuels to fuel markets. Biofuels are liquid substitutes to gasoline and diesel that are derived from grains, sugar, and oil seeds.[8] These fuels can be blended with gasoline up to a level of 10% with no modification to existing automobiles. Higher blend ratios (e.g., E85 which has

[8]For a comprehensive survey on biofuels, their economic impacts, as well as their environmental implications, see Rajagopal and Zilberman (2008).

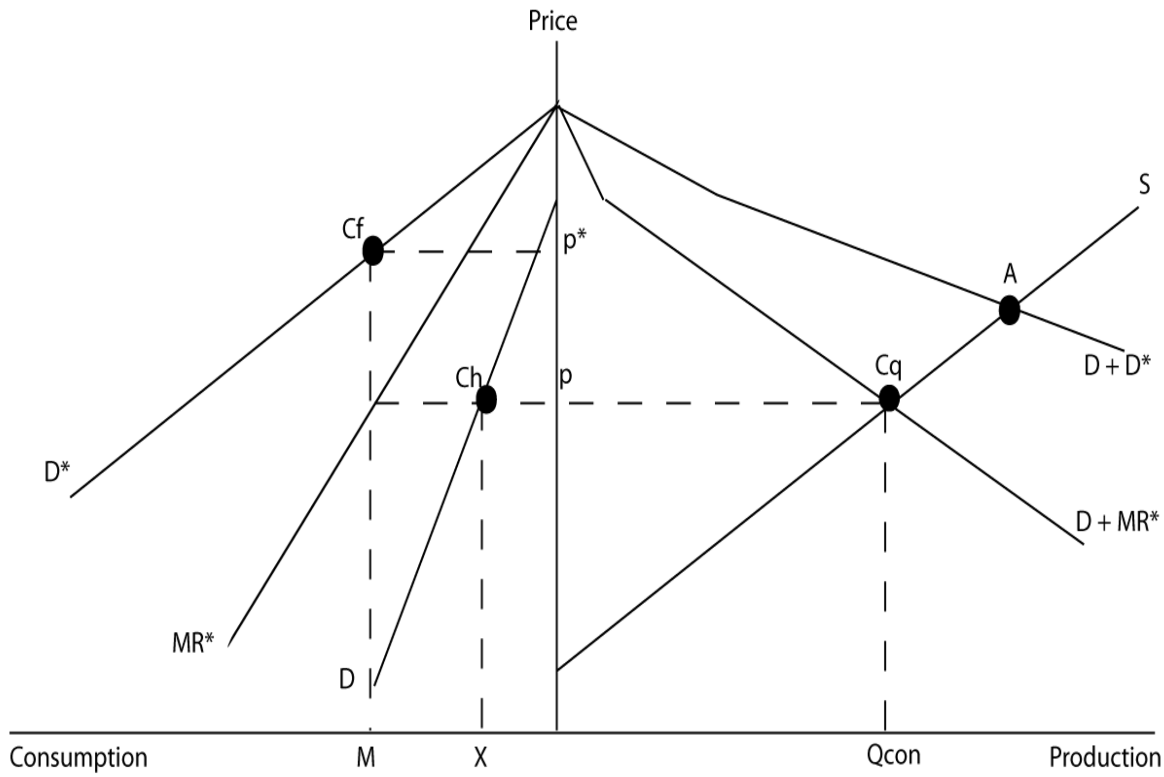

Figure 3: Export tax

85% ethanol and 15% gasoline), however, do require modification to the combustion engine. That said, with the exception of Brazil, current supply largely comprises of blends below 10% ethanol. Therefore, we assume gasoline and ethanol are perfect substitutes.[9]

The global biofuel industry is assumed competitive. About 50% of biofuel production costs come from the feedstock itself (National Renewable Energy Laboratory website), which is purchased from multiple (farm) locations (for example, 72% of farms in the U. S. plant less than 250 acres of corn per farm). The bio-refinery uses the feedstock to produce a spectrum of products (i.e., food, feed, materials, and chemicals) and energy (fuels, power, and heat), and its scale of operation is much smaller than a petroleum refinery. For instance, the average capacity of a bio-refinery in the United States is 47 million gasoline-equivalent gallons (GEG) per year and there are about 200 U. S. bio-refineries,[10] whereas the capacity of the average oil refinery in the United States is 871 million gasoline gallons, of which there are about 143. In Brazil, on the other hand, there were 378 ethanol plants operating by July 2008, 126 dedicated to ethanol production and 252 producing both sugar and ethanol. We, therefore, assumed the biofuel industry behaves competitively, and is produced by producers located in the country F, i.e., the oil-importing country.

To illustrate the welfare implications of the CON model, when biofuels are introduced to the fuel

[9]Although a binding mandate may introduce a wedge between the ethanol and the gasoline price (de Gorter and Just, 2009; among others), to simplify the analysis we elected to equate these prices after correcting for energy intensity. To this end, during most of 2007 biofuel mandates were not binding.

[10]The data were collected on July 14, 2009, from http://www.ethanolrfa.org/industry/locations/

market, we develop an example that uses linear demand and marginal cost curves, denote the quantity of biofuels supplied and consumed in the oil-importing country as $Q_{biofuel}$ and $M_{biofuel}$, respectively, and assume oil-exporting countries behave like a leading firm, treating the biofuel industry as a competitive fringe that takes the international fuel price as given. In other words,

$$
\begin{aligned}
D &: \quad p = \beta_0 - \beta_1 \cdot X_{oil}, \\
D^* &: \quad p^* = \beta_0^* - \beta_1^* \cdot M_{fuel}, \\
MC &: \quad MC = \alpha_0 + \alpha_1 \cdot Q_{oil}, \\
& \quad\;\; X_{oil} + M_{fuel} = Q_{oil} + Q_{biofuel}, \text{ and} \\
& \quad\;\; M_{fuel} = M_{oil} + M_{biofuel}.
\end{aligned}
\tag{1}
$$

Subscript (oil) or (biofuel) denotes the feedstock used to produce the fuel. Biofuels are produced and consumed only in the oil-importing country, as observed in 2007. When calibrating the model, all quantities are adjusted to gasoline-equivalent quantities. In addition, assume α_0, α_1, β_0, β_1 ,β_0^*, and $\beta_1^* > 0$.

Fig. 4 depicts the fuel market, which now includes biofuels (the red curves). The supply of biofuels reduces demand for fossil fuel to $D^{*'}$, such that $D^{*'} = D^{-1}_{fuel}(M_{fuel}) - Q_{biofuel}$. The larger the international price of fuel, the larger is the quantity supplied of biofuels and, therefore, the smaller is the quantity of fossil fuel imported to country F, and thus the gap between $D^{*'}$ and D^* widens as the price increases.

In equilibrium, the quantity supplied equals the quantity demanded such that $D + MR^{*'}$ equals MC, where $MR^{*'} = \partial(p^* \cdot M_{oil})/\partial M_{oil}$. Hence, price in country H declines, as does the price in country F. Note that although fuel prices in country F, gasoline consumption in country F, and total gasoline consumption go down, gasoline consumption in country H goes up. With biofuel, country H, i.e., the oil-exporting country, consumes more gasoline, as illustrated by the left-hand side of Fig. 4, i.e., $p^{*'} < p^*$ and $M' < M$ whereas $X' > X$. The right-hand side of Fig. 4, on the other hand, illustrates that production of fossil fuel (gasoline) goes down with biofuel, i.e., $Q'_{CON} < Q_{CON}$.

Authors modeling empirically the demand for fuels use the linear assumption (Dées et al., 2007; among others), and numerical simulations suggest that the results presented in the paper do not change qualitatively if, instead, we assume constant demand elasticity. Furthermore, an upward-sloping supply function better characterizes the fuel market, in contrast to a constant unit cost function. Whereas the upstream costs for a barrel of oil equivalent in the United States for onshore drilling equals 23.45 US$, it equals 57.20 US$ for offshore drilling; in other words, the marginal cost of a barrel of crude oil increases with the quantity supplied – the first barrel comes from onshore drilling, the last from offshore.

The framework presented above, i.e., the CON model, captures an important stylized fact—that

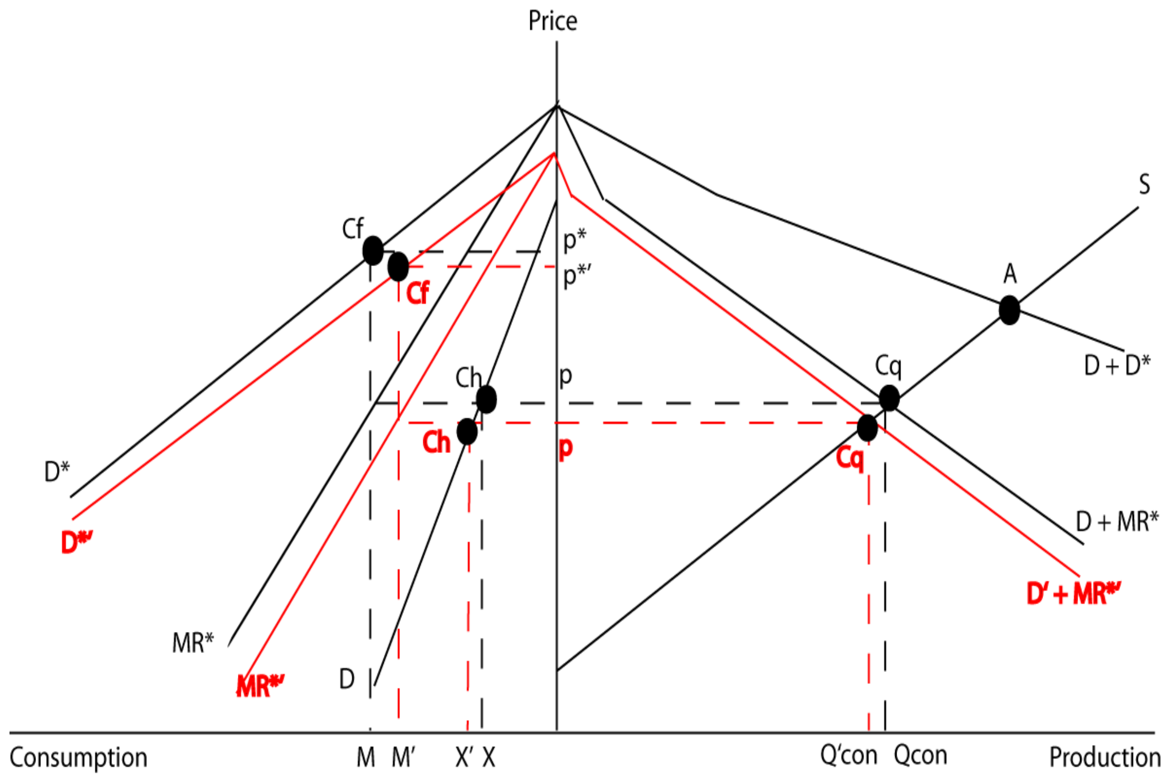

Figure 4: Introducing biofuels to the fuel markets

there is a positive wedge between prices in oil-exporting and oil-importing countries, and that this wedge increases with the introduction of biofuels. It suggests that the introduction of biofuels affects the price of fuel, and the quantities and composition of fuels consumed, and that the magnitude of its impact is influenced by market structure. While theory can predict the qualitative effects of biofuel on fuel markets, to derive policy recommendations, quantitative measures are also required. To this end, we now resort to numerical analysis to quantify the effects of biofuel on fuel markets.

2.1 Calibrating the model

For the calibration, we assumed short-run production is capacity constrained, but is upward sloping in the long run. Specifically, the quantity of biofuel supplied is assumed to be fixed in calibrating the model for 2007, but assume biofuel's supply is upward sloping in Section 4.3 when analyzing the effect of biofuel with a 20% increase in demand for fuel.

We used observed data on quantities and prices, given assumptions on equilibrium behavior, to calibrate the model for 2007. The demand elasticity for fuel η_D is used to compute the slope of country F's demand curve:

$$\beta_1^* = \frac{-p^*}{D^* \cdot \eta_D^*}. \tag{2}$$

Equation (3), together with the equilibrium quantity and prices M and p^*, are used to compute the intercept of the demand function:

$$\beta_0^* = p^* + \beta_1^* \cdot M. \tag{3}$$

We use equilibrium behavior to compute the price in country H, given the annual Western Texas Intermediate price of crude oil. To this end, we know that

$$p = MR^* = \beta_0^* - 2 \cdot \beta_1^* \cdot M_{oil} = 2 \cdot p^* - \beta_0^* \tag{4}$$

The first equality in (**??**) follows from OPEC's equilibrium pricing behavior; the second follows the definition of marginal revenue; the latter uses the fuel demand curve in country H to substitute for X_{fuel}.

Building on demand equations computed above, we compute marginal cost-using equilibrium behavior using assumptions on supply elasticity η_S (recall that p denotes domestic price in country H):

$$\alpha_1 = \frac{S(p)}{p} \text{ and } \alpha_0 = Q_{oil} - \alpha_1 \cdot p. \tag{5}$$

Note that each model implies different equilibrium behavior, and therefore different marginal cost curves. Whereas in competition, we equate demand and supply, in the COF model we equate marginal revenue to marginal cost. Unlike the other two models, the CON model equates $D + MR^*$ to marginal cost. The demand curve for country H, but not country F, is also sensitive to the model chosen. This also introduces further differences between the CON model, and the COF and competition models.

3 Data

Building on the assumptions made above, we calibrated the model using data on crude oil and biofuels in 2007 (see Table 1). Specifically, we use price and quantity data to calibrate demand and supply equations under the alternative models.

To convert crude oil to gasoline, we note that a barrel of crude oil equals 42 gallon, of which 19.5 gallons are used to produce gasoline. Put differently, 46% of a barrel of crude oil is allocated to gasoline production. The usage of the remaining 54% includes distillate fuel oil (heating and diesel fuels), kerosene-type jet fuel, liquefied refinery gases, still gas, coke, asphalt and road oil, and petrochemical feedstock.[11] We use this ratio to convert barrels of crude oil to gasoline-equivalent

[11] http://www.txoga.org/articles/308/1/WHAT-A-BARREL-OF-CRUDE-OIL-MAKES

gallon (GEG). We also used this ratio to compute the international price of a gallon of gasoline, i.e., $(0.46 \cdot 72) / (0.46 \cdot 42) = 1.7143$ US$. Note that we focus on the international price of gasoline (not the price at the pump), because we use global quantities of GEG imported and consumed by oil-importing countries.

We assume a gallon of ethanol is equivalent to 2/3 a gallon of gasoline, whereas a gallon of biodiesel is equivalent to 1.04 gallons of gasoline.[12] The 2007 data therefore imply that global ethanol and biodiesel GEG equal 10.9 billion gallons.

Finally, to compute fuel's contributions to greenhouse gases, we recognize that every fuel feedstock has its own CO_2 intensity. Therefore, total CO_2 emissions depend on the biofuel feedstock used. Given a biofuel feedstock, to compute total CO_2 emissions we multiplied for each feedstock the tons of CO_2 equivalent per megajoule (MJ)[13] times the feedstock energy density in MJ times the quantity consumed in equilibrium.

Table 1 summarizes the values and parameters used to calibrate the models. Note that the numerical analysis presented below builds on data confined to crude oil, biofuels, and biodiesel, and does not include alternative fossil fuel such as heavy oil. Adding alternative fuel sources introduces additional complexity, but does not qualitatively change the results.

4 The numerical analysis

We now develop these measures. Building on price and quantity data for 2007, we calibrate the competitive, the COF, and the CON models. Parameters in these analyses are price elasticity of supply and demand. For example, fuel markets are characterized by low demand elasticity, where a given relative change in prices results in a relatively small change in quantities. We, therefore, choose a residual import demand elasticity (the import demand elasticity observed by an exporting country) of -1.25, -1.5, -1.75, and -2.0 and crude oil supply elasticity of 0.10. In Section 4.1, we use this structure to estimate the impact of biofuel on fuel markets and the environment.

4.1 The baseline model: CON

Biofuels cause oil prices in importing country to decline by 1.61% to 1.21% (Table 2). The wedge, on the other hand, increases by 2.09% to 2.52% (Table 2). The introduction of biofuels creates pressure

[12] http://en.wikipedia.org/wiki/Gasoline_gallon_equivalent

[13] To convert gallons of gasoline, ethanol, or biodiesel to megajoule we use the Lower Heating Value (LHV), which are 32.0, 33.3, and 21.1, respectively. Alternatively, we can use Higher Heating Value, which includes condensation of combustion products, and for biomass is 6% to 7% higher than the LHV. However, because there is no attempt to extract energy from hot exhaust gases, LHV is more appropriate (see http://bioenergy.ornl.gov/papers/misc/energy_conv.html).

to reduce prices. Oil-exporting countries mitigate the cost by redistributing benefits from biofuel to domestic fuel consumers. It reduces exports, but increases domestic consumption. This ability to influence prices, however, declines as demand becomes more elastic, wherever larger levels of biofuel yield more elastic demand functions.

On the other hand, introducing 10.9 billion ethanol and biodiesel GEG to oil markets reduce gasoline consumption by 1.440 to 1.055 billion gallons (Table 3). At the same time, the rebound effect resulting from lower fuel prices contributes to a net increase of 9.5 to 9.9 billion GEG. The reduction in gasoline consumed depends on the supply elasticity, such that larger supply elasticity implies larger reduction in gasoline consumption and a smaller rebound effect. However, independent of the elasticity, the introduction of biofuels offsets the reduction in gasoline consumption and replaces dirty fuel with clean fuel. The shift in the energy composition toward renewable energy alternatives not only forces oil-exporting countries to reduce production, but also reduces domestic gasoline prices.

Next, we compare the economic gains from biofuel. In this analysis we assume that corn ethanol is profitable at 1.49 US$ a gallon (consistent with the EPA's Notice of Proposed Rule Making for the Renewable Fuel Standard 2 – RFS2).[14] Assuming import demand elasticity -1.25, the implied marginal cost in equilibrium is 0.34 US$,[15] and it is equal to the domestic price in the oil-exporting countries. This is consistent with the Energy Information Administration (EIA) (2008)[16] report that the upstream cost of a barrel of crude oil in the Middle East was 14.85 US$ between 2005 and 2007, which equals 0.35 US$ per gallon of gasoline (14.85/42 = 0.35). Our analysis also suggests that the introduction of biofuels reduced the amount paid by consumers in country F for oil imported from country H by 16.44 to 10.89 billion US$, for import demand elasticity -1.25 to -2.0, respectively.

In what follows, we assume the CON model correctly captures the global fuel markets, and ask how much do we error if we choose an alternative model, i.e., competition or COF.

4.2 The implications of picking the wrong model

How much do we error if, instead of modeling CON, we assume a competitive or COF model? We show that the distribution of resources among groups and nations, as well as carbon emitted from energy consumption, are substantially different among various market structures. Selection of the wrong model may lead to (big) measurement errors.

The competition model *overestimates* the price effect of biofuel on international prices by 25.65% to 8.92% (Table 2). A COF *overestimates* the price effect by 16.56% to 3.68%. On the other hand, a

[14] http://www.epa.gov/OMSWWW/renewablefuels/rfs2-nprm-preamble-regs.pdf

[15] Although the empirical literature suggests inelastic global demand for crude oil, the elasticity of the residual demand curve faced by a single exporting country should be higher. Similar elasticities were used in Hamilton (2008), when evaluating Saudi Arabia's pricing behavior.

[16] http://tonto.eia.doe.gov/dnav/pet/pet_pri_wco_k_w.htm

competitive model *underestimates* the effect of biofuels on gasoline consumption by about 40% (Table 3), whereas the COF model *overestimates* the effect by between 16.56% and 3.68%. The differences stem from the calibration; especially from the way we calculated marginal costs. Whereas with CON marginal costs are between 0.34 and 0.86 US$ per gallon, they are 1.71 US$ with competition (recall that the international price of gallon of gasoline equals 1.71 US$), and 0.31 to 0.81 US$ with COF.

With CON, domestic consumption in oil-exporting countries matters. Whereas with competition or COF, consumption in exporting countries increased by less than 220 million GEGs due to the introduction of biofuel, it increased by more than 500 million gallons with CON. Oil-exporting countries increase consumption of cars. These considerations are overlooked when COF or competition behavior is assumed, and the bias introduced becomes more significant as GDP per capita in oil-exporting countries increase (e.g., car ownership increases exponentially with GDP per capita once countries pass the 5,000 US$ mark). Although consumption of crude oil in the Middle East, Algeria, and Venezuela together currently amounts to 10% of total world consumption of crude oil, consumption grew from 2005 to 2006 by 3.5%, 3.4%, and 4.3%, respectively. In contrast, consumption in the rest of the world grew by an insignificant 0.7%.

The wrong specification leads to overestimation of carbon emission, and may mislead policymakers. Difference in gasoline consumptions between the three scenarios suggests differences in estimation of carbon emission (Table 4). The competitive model *underestimates* by more than 37% the reduction in carbon emission due to biofuel because it underestimates the reduction in gasoline consumption. The COF model, on the other hand, may underestimate or overestimate the reduction in carbon due to biofuel, and the difference is a function of the demand elasticity. Whereas at a demand elasticity of -1.25 it overestimates the reduction in carbon by 17%, it underestimates the reduction by more than 12% when the elasticity of demand is -1.75. The difference also depends on the gasoline supply elasticity. Larger elasticity implies bigger reductions in gasoline consumption.

Although the competitive model overestimates consumers' benefit from biofuel in an importing country (country F), the competitive model underestimates the benefits to consumers in the exporting country (country H). The competitive model overestimates total monetary benefit from biofuel to importing country by 20.5% to 6.7%, whereas the COF model overestimates the benefit from biofuel to the importing country by 13.3% to 2.8%.

The competitive and COF models underestimate the costs of biofuel to oil-exporting countries due to reduction in crude oil production. The competitive model underestimates the cost by 10.4% to 6.5% (Table 5). The COF model underestimates the cost by 0.93% to 0.40%.

4.3 Increasing demand for fuel augments the effect of biofuel on the fuel markets

If history is indicative to the future of fuel markets, then demand for energy, especially fuel, will grow substantially in the coming decades. To this end, total world demand for crude oil increased by more than 18% in the last 10 years (BP statistical review 2008). During September 2008, the EIA baseline scenario (International Energy Outlook 2008) predicted that world marketed energy consumption will grow by 50% between 2005 and 2030. In their report, the EIA concluded that global energy demand would continue to grow, despite sustained high world oil prices.

We, therefore, considered the case where the importing country's demand for fuel increased by 20%; which is about the growth in global demand for crude oil from 1998 to 2008. Similar to the short-run import demand elasticity that the Hamilton (2008) analysis suggests Saudi Arabia observes, we assumed the oil-exporting country sees an import demand elasticity of -1.25, and allowed the biofuel supply elasticity to range from 5 to 20. Thus, unlike the earlier section here, we model the long-run supply curve for biofuel. The biofuel supply elasticity implies that in the absence of any technological change, and as long as the elasticity is above 8.5, biofuel production meets the RFS2 volumetric mandate of 36 billion gallons in 2022. We also assumed for the simulation that biofuel is profitable at a price above 1.7143 US$.

Under these assumptions, we show that with an increase in demand for fuels, the effect of biofuels on fuel markets becomes much more substantial in absolute terms. Assuming the increase in fuel consumption comes only from gasoline (the amount of biofuel produced is fixed at the 2007 level) implies fuel prices in oil-importing countries increase by 30.5%, whereas gasoline consumption increases by 2.8% globally, but by 5.7% in oil importing countries.

Assuming a 20% increase in demand for fuel, together with the lowest biofuel supply elasticity of 5, implies that biofuels reduce international prices by 2%, but reduce domestic prices in oil-exporting countries by 8%. Moreover, biofuel decreases global consumption of gasoline by 0.4%, but it increases total fuel consumption in gasoline-equivalent units (gasoline and biofuel consumption) by 2.2%—the rebound effect. On the other hand, the sum of surplus to consumers from fuel consumption and profits from biofuel production increases by more than 12%. Finally, the gains from reducing carbon are about 10 billion US$,[17] if (i) biofuels are produced using switchgrass (a second generation feedstock which, according to the RFS2, has negative direct CO_2 emissions—see Table 1), and (ii) the cost of a ton of carbon is 30 US$. The potential benefits from biofuel over time are enormous; the challenge, however, is to produce such large quantities of biofuel in a sustainable, environmental, and economic way.[18]

[17] See Section 3 and Table 1 for the equation used to compute this value.
[18] For more on sustainability of biofuels, see Khanna et al. (2008).

Finally, choosing the wrong model yields large measurement errors. If we use a competitive model and the lowest biofuel supply elasticity of 5, then the introduction of biofuels reduces gasoline consumption by only 10.29 billion gallons—44% less than the reduction of gasoline consumption implied by the CON model. Moreover, the competitive model suggests prices decline by 17.12%, in contrast to the 1.5% suggested above when the CON model was used.

5 Policy implications and concluding remarks

In this paper, we assume oil-rich countries pursue cheap oil policies, which derive a wedge between domestic and foreign prices by restricting the supply of oil in oil-importing countries. We contrast the findings derived assuming a CON model with those derived when a competitive or COF model is used, and we illustrated that using the wrong model introduces large quantitative, as well as qualitative, biases into the analysis. The introduction of biofuels affects fuel prices and quantities, distribution of economic surplus, and climate change. Failure to incorporate OPEC into the analysis will result in poor impact assessment.

In our empirical analysis, we illustrated that competition overestimates the price effect and underestimates the quantity effect due to the introduction of biofuels. Large differences in the amount of gasoline consumed under the alternative models translate to large differences in carbon savings. Assuming a ton of carbon costs 30 US$, carbon savings are 40% higher with CON, in contrast to competition. Although these differences depend on the elasticity, especially the elasticity of crude-oil supply, the differences remain large under plausible scenarios (recall that introducing biofuels causes gasoline quantities to decline more under the CON model, when compared to competition). Conceptually, OPEC responds to the introduction of biofuels by reducing exports and increasing domestic consumption, resulting in a decline in total gasoline consumption above and beyond the decline suggested by the competitive model. Then, if the GHG emissions of biofuel are significantly lower than the emissions attributed to gasoline consumption, the introduction of biofuels results in net GHG savings.

In addition, the effect of biofuel on consumers of gasoline, and the distribution of benefits across different consumer groups, is different from the benefits derived using the competitive or the COF model. In contrast to the competitive model, consumers in importing countries gain less because OPEC uses its market power to shift the gains from biofuel to its domestic consumers. Here, we find that fuel consumers benefited from the introduction of biofuel, but less when its production is induced by mandates.

We predict biofuels in the future will become a key factor in the composition of fuel feedstock. To this end, we used a plausible scenario, where fuel demand grew by 20%, to illustrate the importance

of biofuels. Trying to set policy and regulation, and therefore creating the right incentives for biofuel production, is crucial for us to obtain energy security and mitigate emissions of greenhouse gases. Getting the right policy hinges on the economic and environmental analysis used.

For the reasons mentioned above, we argue that OPEC's behavior should be modeled to any welfare analysis contributing to the food-versus-fuel debate. In future work we plan to pursue this avenue further, and illustrate how introducing OPEC to the analysis affects biofuels contribution to the 2007/08 food inflation.

Table 1. The model parameters	
	Value
2007 quantity and price data	
Quantity of gasoline consumed by country H	6.2 million barrels a day
Quantity of gasoline consumed by country F	54.8 million barrels a day
Price of gasoline	1.7143 US$
Global quantity of ethanol consumed	13.5 billion GEG a year
Global quantity of biodiesel consumed	6.16 million tones a year
Parameters used to compute CO_2 emissions	
Ethanol energy density in MJ per liter	21.1
Biodiesel energy density in MJ per liter (vegetable oil)	33.3
Gasoline energy density in MJ per liter	32.0
Gram of CO_2 equivalent per MJ of gasoline	95.6
Gram of CO_2 equivalent per MJ of sugarcane	50
Gram of CO_2 equivalent per MJ of corn stover*	-15
Gram of CO_2 equivalent per MJ of switchgrass*	-23

* Source: RFS2

Table 2. The price effect of biofuel in US$					
		-1.25	*-1.5*	*-1.75*	*-2*
Levels: US$					
	Competition	-0.0444	-0.0376	-0.0326	-0.0288
	Cartel	-0.0412	-0.0353	-0.0308	-0.0274
	CON				
	Exporting country	-0.0707	-0.0654	-0.0587	-0.0529
	Importing country	-0.0354	-0.0327	-0.0294	-0.0264
	Wedge	0.0354	0.0327	0.0294	0.0264
Percent					
	Competition	-2.52%	-2.15%	-1.87%	-1.65%
	Cartel	-2.35%	-2.02%	-1.77%	-1.57%
	CON				
	Exporting country	-17.10%	-10.27%	-7.40%	-5.81%
	Importing country	-2.02%	-1.87%	-1.68%	-1.52%
	Wedge	2.65%	2.95%	3.09%	3.18%
Percent change relative to CON					
	Competition	25.48%	14.91%	11.00%	8.86%
	Cartel	16.45%	7.83%	5.02%	3.65%

Table 3. Fuel consumption and biofuel (million of gallons)

		Demand elasticity	***-1.25***	***-1.5***	***-1.75***	***-2***
Levels						
	Competition					
		Exporting country	215.23	182.31	158.13	139.61
		Importing country	-1,062.30	-899.80	-780.44	-689.04
		Total	-847.04	-717.49	-622.31	-549.43
	Cartel					
		Exporting country	199.75	171.08	149.61	132.93
		Importing country	-1,772.00	-1,517.60	-1,327.20	-1,179.20
		Total	-1,572.20	-1,346.60	-1,177.60	-1,046.20
	CON					
		Exporting country	1,715.30	951.96	664.80	512.98
		Importing country	-3,065.40	-2,200.80	-1,786.10	-1,522.40
		Total	-1,350.10	-1,248.80	-1,121.30	-1,009.40
	Biofuel		10,927.90	10,927.20	10,927.20	10,927.80
Percent change relative to CON						
	Competition		-37.26%	-42.55%	-44.50%	-45.57%
	Cartel		16.45%	7.83%	5.02%	3.65%
The rebound effect						
	Competition		10,080.86	10,209.71	10,304.89	10,378.37
	Cartel		9,355.70	9,580.60	9,749.60	9,881.60
	CON		9,577.80	9,678.40	9,805.90	9,918.40

Table 4. The cost of carbon					
Reducing the cost of carbon – millions of US$					
Feedstock		**-1.25**	**-1.50**	**-1.75**	**-2.00**
Sugarcane					
	Competition	$1,045.80	$1,094.20	$1,129.76	$1,156.99
	Cartel	$774.87	$859.17	$922.32	$971.37
	CON	$857.85	$895.68	$943.35	$985.14
Advance biofuel - low					
	Competition	$422.13	$470.53	$506.09	$533.32
	Cartel	$151.20	$235.50	$298.65	$347.70
	CON	$234.18	$272.01	$319.68	$361.47
Switchgrass					
	Competition	-$987.21	-$938.81	-$903.25	-$876.02
	Cartel	-$1,258.14	-$1,173.84	-$1,110.69	-$1,061.64
	CON	-$1,175.16	-$1,137.33	-$1,089.66	-$1,047.87

Table 5. Disaggregating the benefits from biofuel					
Changes in economic surplus - millions of USD					
Change in:	*Demand elasticity*	***-1.25***	***-1.5***	***-1.75***	***-2***
Consumer surplus: Importing country	**Competition**	13,311.00	11,272.00	9,774.70	8,628.60
	Cartel	12,368.00	10,588.00	9,256.50	8,222.20
	CON	10,643.00	9,830.80	8,820.70	7,937.30
Consumer surplus: Exporting country	**Competition**	1,471.10	1,246.70	1,081.70	955.31
	Cartel	1,365.60	1,170.10	1,023.60	909.67
	CON	2,291.70	2,144.80	1,934.20	1,745.20
Total change in consumer surplus	**Competition**	14,782.00	12,519.00	10,856.00	9,583.90
	Cartel	13,733.00	11,758.00	10,280.00	9,131.90
	CON	12,935.00	11,976.00	10,755.00	9,682.50
PS from biofuel production	**Competition**	2,450.90	2,450.90	2,450.90	2,450.90
	Cartel	2,450.90	2,450.90	2,450.90	2,450.90
	CON	2,450.90	2,450.90	2,450.90	2,450.90
Producer surplus: Exporting country	**Competition**	-14,539.00	-12,313.00	-10,678.00	-9,426.60
	Cartel	-15,816.00	-13,218.00	-11,353.00	-9,949.10
	CON	-23,192.00	-21,449.00	-19,255.00	-17,331.00
Total change in producer surplus	**Competition**	-12,089.00	-9,862.40	-8,227.40	-6,975.70
	Cartel	-13,365.00	-10,767.00	-8,902.20	-7,498.20
	CON	-20,741.00	-18,998.00	-16,804.00	-14,880.00
Export tax revenues		6,300.50	7,172.90	6,936.90	6,508.10
	Producer surplus plus revenues	-16,891.50	-14,276.10	-12,318.10	-10,822.90
Total gain to importing country					
	Competition	15,761.9	13,722.9	12,225.6	11,079.5
	Cartel	14,818.9	13,038.9	11,707.4	10,673.1
	CON	13,093.9	12,281.7	11,271.6	10,388.2
Total gain to exporting country					
	Competition	-13,067.90	-11,066.30	-9,596.30	-8,471.29
	Cartel	-14,450.40	-12,047.90	-10,329.40	-9,039.43
	CON	-14,599.80	-12,131.30	-10,383.90	-9,077.70